Projecting tidal marsh response to sea-level rise using local site conditions San Diego Bay National Wildlife Refuge: Sweetwater Unit

U.S. Geological Survey, Western Ecological Research Center
Coastal Ecosystem Response to Climate Change Program

Data Summary Report Prepared for the U.S. Fish and Wildlife Service

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EXECUTIVE SUMMARY

- Sweetwater marsh is part of the San Diego Bay National Wildlife Refuge Complex. Located in Chula Vista, California, it is the largest remaining salt marsh on San Diego Bay. We collected baseline elevation, tidal inundation, and vegetation on 68 hectares of this 128-hectare marsh to develop sea-level rise (SLR) and vegetation response models to 2110. Accretion rates were determined with sediment core data.

- We used Real-Time Kinematic Global Positioning System (RTK GPS; $\pm$ 2 cm measured vertical accuracy) to conduct on-the-ground elevation surveys. Vegetation was surveyed at a quarter of elevation points within 0.25 m^2 quadrats for species composition, percent cover, and height. We established water level monitoring stations at two locations to capture local annual variation in tidal inundation and to determine elevation relative to site-specific tidal datum.

- A total of 1,156 elevation measurements were collected and interpolated in ArcGIS 10.2.1 (Kriging method) into a continuous 5 x 5 m grid cell raster. Mean root-mean-square (RMS) error for all interpolations was 0.11 and the model mean standard error was 0.12, showing a good measure of accuracy for our elevation models.

- A total of 274 vegetation plots were surveyed, and 15 plant species were recorded. *Sarcocornia pacifica* was the most common species surveyed, occurring at 64 percent of vegetation plots.

- Three sediment cores were collected along an elevation gradient at Sweetwater marsh to determine historic accretion rates with horizon marker dating techniques (^{137}Cs). Percent organic matter, porosity, compaction, and decomposition were incorporated with accretion rates, elevation, and tidal range data and were inputs into the Wetland Accretion Response Model for Ecosystem Resilience (WARMER, Swanson et al. 2013) used to assess marsh persistence with sea-level rise.

- Vegetation communities were categorized based on observed elevation relative to local tidal datum to develop marsh zones for model interpretation. Marsh zones were defined as below mean sea level (MSL) (< 0 cm MSL), unvegetated (0 – 40 cm MSL), low marsh (41 – 66 cm MSL), mid marsh (67 -86 cm MSL), high marsh (> 87 cm MSL).

- Currently Sweetwater is characterized by mid and high marsh vegetation (49 and 33 percent of total area respectively). Results from the WARMER modeling suggested that under mid (+93 cm) SLR scenarios, the marsh can keep pace until 2050; thereafter, low marsh becomes dominant by 2070 (60 percent) and mudflat increases in extent by 2110 (34 percent). Results under high (+166 cm) SLR scenario show that the marsh can keep pace until 2040; thereafter, low marsh becomes dominant by 2050 (55 percent) and by 2110 the marsh is 91 percent mudflat and 8 percent below MLLW.

1. INTRODUCTION

Climate change effects for coastal ecosystems include projected changes in mean and extreme ambient temperatures, precipitation patterns, ocean temperature and acidity, extreme storm events, and sea-level rise (SLR; Cayan et al., 2006; Hansen et al., 2006; IPCC, 2007, NRC, 2012). Projections of mean SLR to the year 2110 are uncertain, due to the high uncertainty associated with the levels of future CO_2 concentrations, ocean processes, and melting ice-sheet dynamics (Mouginot et al., 2014). However, global sea level has risen 1.8 millimeters per year (mm/year) between 1961 and 1993, and 3.1 mm/year since 1993 (IPCC, 2007). Recent southern California SLR projections range from 44 - 166 cm by 2100, with a mean increase of 93 cm (NRC, 2012).

Although global in distribution, the extent of tidal marshes is limited to the low wave intensity intertidal zones of temperate estuaries, with 16,000 square kilometers (km^2) found in North America (Greenberg et al., 2006). Tidal marshes are highly productive ecosystems (Penfound, 1956; Westlake, 1963) that provide important habitat for small mammals, fish, birds, and invertebrate communities (Massey, 1984; Desmond et al., 2000; Thorne et al., 2012; Tsao et al., 2009). They also provide numerous ecosystem services such as carbon sequestration, wave attenuation, water filtration, and protection from flooding and storm surge. These productive systems have prolonged periods of flooding which can limit decomposition (Battle et al., 2001), making them potentially favorable areas for carbon storage (Craft et al., 1993; Frockling et al., 2001; Chimner et al., 2002). Salt marshes can mitigate aerobic decomposition of subsided organic soils as well as establish conditions favorable for carbon storage. Rates of carbon storage result from the balance of inputs and losses, both of which are affected by wetland hydrology. Tidal marshes also act as a water filtering system for surrounding watersheds. Pollutants such as herbicides, pesticides, heavy metals, excess sediments and nutrients are filtered out of water as it moves through a marsh (USEPA, 1993).

In addition, estuaries and their surrounding tidal marshes act as buffer zones from storm surges by absorbing water and slowing water velocity and wave energy which can protect coastal areas, inland habitats and human communities from floods and storm surges. Estuarine habitats also protect streams, river channels and coastal shores from excessive erosion caused by wind and wave action and tidal water (Barbier et al., 2011).

Vegetation plays an important role in marsh development by trapping suspended sediment and supplying below and above ground organic matter (Callaway et al.,1996; DeLaune et al., 1990; Geden et al., 2011; Stevenson et al., 1988; Stempf, 1983). The vertical development of the marsh is dependent on the velocity of suspended sediment concentrations and water flow across the marsh surface (Boorman, 2003). Vegetation reduces the water velocity, thus enhancing the deposition of sediment and reducing erosion (Leonard et al., 1995). Once vegetation is established, the rate of sedimentation (a component of accretion) will increase as more of the incoming sediment is intercepted and trapped by the increased surface roughness (Stumpf, 1983; Stevenson et al., 1988). In addition, vegetation reduces the re-suspension of deposited material and reduces scour of the marsh surface (Allen et al., 1992). Vegetation increases organic matter within a marsh by the accumulation of litter on the marsh surface as plants grow and through root growth below the surface (Allen et al., 1992). There is some consolidation of the accumulated deposits but collectively these processes lead to a steady build-up in the surface elevation of the marsh and the stability of the deposited material which can be measured as accretion. The components necessary for the development and growth of a tidal marsh include 1) a relatively stable tidal area with available sediment supply, and sufficiently low water velocity for sediment to deposit on the surface; and 2) a supply of seeds or other propagules for the establishment of vegetation cover (Boorman, 2003).

Marshes are dominated by plant communities that have varying tolerance to tidal inundation and salinity, resulting in zonation along the elevation and inundation gradient (Mancera et al., 2005). The lower littoral zone is inundated twice daily with tidal flows while the upper littoral zone is partially inundated only during high tides (Purer 1942, p. 93). Marshes are particularly vulnerable to SLR because variation in tidal depth and duration plays a major role in structuring these plant communities (Brittain et al., 2012). Marshes can keep pace with changes in local sea level through accretion processes that include sediment deposition and organic matter accumulation (Morris et al. 2002, Geden et al., 2011) if suspended sediment concentrations and organic production are high enough (Kirwan et al., 2010). However, marshes may be lost if SLR outpaces vertical accretion processes, resulting in the loss of marsh plant communities (Morris et al., 2002, Callaway, 2007).

Southern California tidal marshes have been heavily modified and affected by coastal development and urbanization with as much as 75 percent of historic tidal marshes lost region wide and 90 percent lost in San Diego Bay (Larson, 2001). Over the past 150 years, dredging and filling operations have resulted in the loss of 42 percent of San Diego Bay's historic shallow subtidal habitat, 84 percent of its intertidal mudflat habitat, and 70 percent of its salt marsh habitat (USFWS, 2006). With the substantial loss of salt marsh habitat in southern California it is important to determine the effects of climate change on the remaining marshes.

This study is part of a larger climate change program looking at SLR and storm effects across a latitudinal gradient along the Pacific coast in Washington, Oregon, and California (see http://www.werc.usgs.gov/cercc) . Our studies are directed at a bottom-up approach to evaluate SLR and storm effects for individual parcels and to provide detailed ground information useful in assessing local impacts, but are comparable across sites and regions. This information can inform the development of management strategies to conserve natural resources in light of climate change. The objectives of this study were to (1) inventory plant species composition and relationship to elevation and tidal ranges; (2) inventory elevation and marsh accretion rates, and (3) use high resolution digital elevation models (DEMs) to develop SLR marsh and vegetation response models to 2110 for the Sweetwater Marsh unit (hereafter Sweetwater) of the San Diego Bay NWR using the Wetland Accretion Rate Model for Ecosystem Resilience model (WARMER: Swanson et al., 2013).

2. STUDY AREA

Sweetwater is a 128-hectare (ha) tidally influenced marsh that is part of the San Diego Bay National Wildlife Refuge Complex. Sweetwater is in Chula Vista, California, at the mouth of the Sweetwater River (Fig. 1). As the largest remaining salt marsh in San Diego Bay, it provides important habitat for wintering waterfowl and shorebirdsas well as nesting habitat for several endangered bird species including the California Least Tern (*Sternula antillarum browni*), Belding's Savannah Sparrow (*Passerculus sandwichensis beldingi)*, and the Light-footed Ridgway's Rail (*Rallus obsoletus ssp. levipes*). In addition, Sweetwater fosters endangered salt marsh bird's beak (*Chloropyron maritimum ssp. Maritimum*), and the only known native population of the endangered plant, Palmer's Frankenia (*Frankenia palmeri*).

Calilfornia Least Tern (*Sternula antillarum browni*)

The California Least Tern is a colonial species that migrates to breeding areas along the California coast in the spring, then to Central or South American coasts in the fall. As the smallest subspecies of the Least Tern species, it is characterized by a long, slightly decurved bill, black cap, orange legs, and a forked tail (Sibley 2000). Its diet consists exclusively of fish, typically northern anchovy, jacksmelt, topsmelt, and other species (Massey 1974, Atwood and Kelly 1984). Foraging is typically carried out over short distances in calm, narrow estuaries or large bays, and occasionally in the open ocean (USFWS, 2011).

Belding's Savannah Sparrow (*Passerculus sandwichensis beldingi*)

The Belding's Savannah Sparrow resides year-round in the coastal salt marshes of southern California. This subspecies of Savannah Sparrow is a salt marsh endemic, historically ranging from Santa Barbara County, California, in the north, to Baja California, Mexico in the south (American Ornithologists Union 1983, Grinnell and Miller 1944, and Van Rossen 1947). Belding's are ecologically associated with dense pickleweed (*Sarcocornia spp.),* and most nests are found within this species. Breeding territories can be very small, and birds nest semi-colonially or locally concentrated within a larger block of habitat, all of which may appear generally suitable, although pairs are territorial and will deter conspecifics from their nesting territories (Powell, 1993). On the basis of the 2010 surveys, Belding's populations are doing well within their range in California, but especially at Point Mugu Naval Weapons Station, Seal Beach NWR, Bolsa Chica Ecological Reserve, Upper Newport Bay Ecological Reserve, Sweetwater, and Tijuana Slough NWR. Sweetwater had the sixth largest subpopulation in California in 2010 after a 75 percent increase from 2006 (Zembal & Hoffman, 2010). The Belding's Savannah Sparrow was categorized within the mid and high marsh vegetation communities on the basis of its requirements for nesting in dense pickleweed at higher elevations that are less frequently inundated (Powell, 1993).

Light-Footed Ridgway's Rail (*Rallus obsoletus levipes*)

The Light-footed Ridgway's Rail was federally listed as an endangered species in 1970. They are a medium-sized marsh bird that inhabits coastal marshes, lagoons, and maritime environments in southern California of the U. S., and northern Baja California of Mexico. Light-footed Ridgway's Rails are omnivorous and opportunistic foragers, relying mostly on salt marsh invertebrates. They require shallow water and mudflats for foraging, concentrating their efforts in the lower marsh when the tide is out and moving into the higher marsh as the tide advances (Zeiner et al. 1990, p. 174). Nesting habitat includes tall, dense cordgrass (*Spartina foliosa*) and occasionally pickleweed (*Sarcocornia spp*.) in the low littoral zone, wrack deposits in the low marsh zone, and hummocks of high marsh within the low marsh zone (Massey et al. 1984, p. 78).

In a census of 19 Californian marshes during 2007, eight marshes contained 92 percent of the rails counted, two of which were within the San Deigo Refuge Complex, Seal Beach NWR (ranked second) and Tijuana NWR (ranked third). Loss and degradation of habitat threaten the continued existence of the Light-footed Ridgway's Rail, in spite of ongoing management efforts (Zembal et al., 2013).

Salt Marsh Bird's Beak (*Chloropyron maritimum ssp. maritimum*)

Salt marsh bird's beak is an annual hemiparasitic and halophytic plant that has a naturally patchy distribution in sites and is subject only to higher tidal influxes in coastal salt marshes (USFWS, 2009). If suitable host plants or native pollinators are not present, it is unlikely that any *C. maritimum* plants would persist to reproductive maturity (Noe and Zedler, 2000; Parsons and Zedler, 1997). Salt marsh bird's beak was reported from the higher areas, identified as the middle littoral zone by Purer (1942) growing with species of *Sarcocornia, Distichlis, Frankenia, Suaeda*, and *Atriplex*. It was listed as endangered under the Endangered Species Act in 1978 and is currently known to persist in seven coastal salt marshes: San Diego County at Tijuana Estuary (separated into Border Field State Park and Tijuana Slough NWR); Naval Radar Receiving Facility (NRRF) and Sweetwater; Orange County at Upper Newport Bay (State) Ecological Reserve; Ventura County at Naval Base Ventura County, Point Mugu; Santa Barbara County at Carpinteria Salt Marsh; San Luis Obispo County at Morro Bay. After restoration plantings of Salt marsh bird's beak at Sweetwater between 1990 and 1992, individual plants numbered 14,000 in 1995 (USFWS, 2009).

Salt marsh bird's beak, like many marsh endemics, is vulnerable to SLR for three main reasons: 1) the plants are restricted to mid tidal marsh zones; 2) the habitat is subject to hydrological fluctuations, where small changes in inundation could impact the plants; and 3) plants are hemiparasitic on associated salt marsh taxa. This species is categorized within the mid-marsh vegetation community based on the location of its host plants and Purer's 1942 classification.

All of the species discussed above, and others, depend heavily on the presence of tidal marsh for habitat, foraging, refuge, and reproduction, and have the propensity to be greatly affected by SLR as marsh habitat is lost. Our study focused on 63 ha of salt marsh within the Sweetwater marsh unit (Fig. 1).

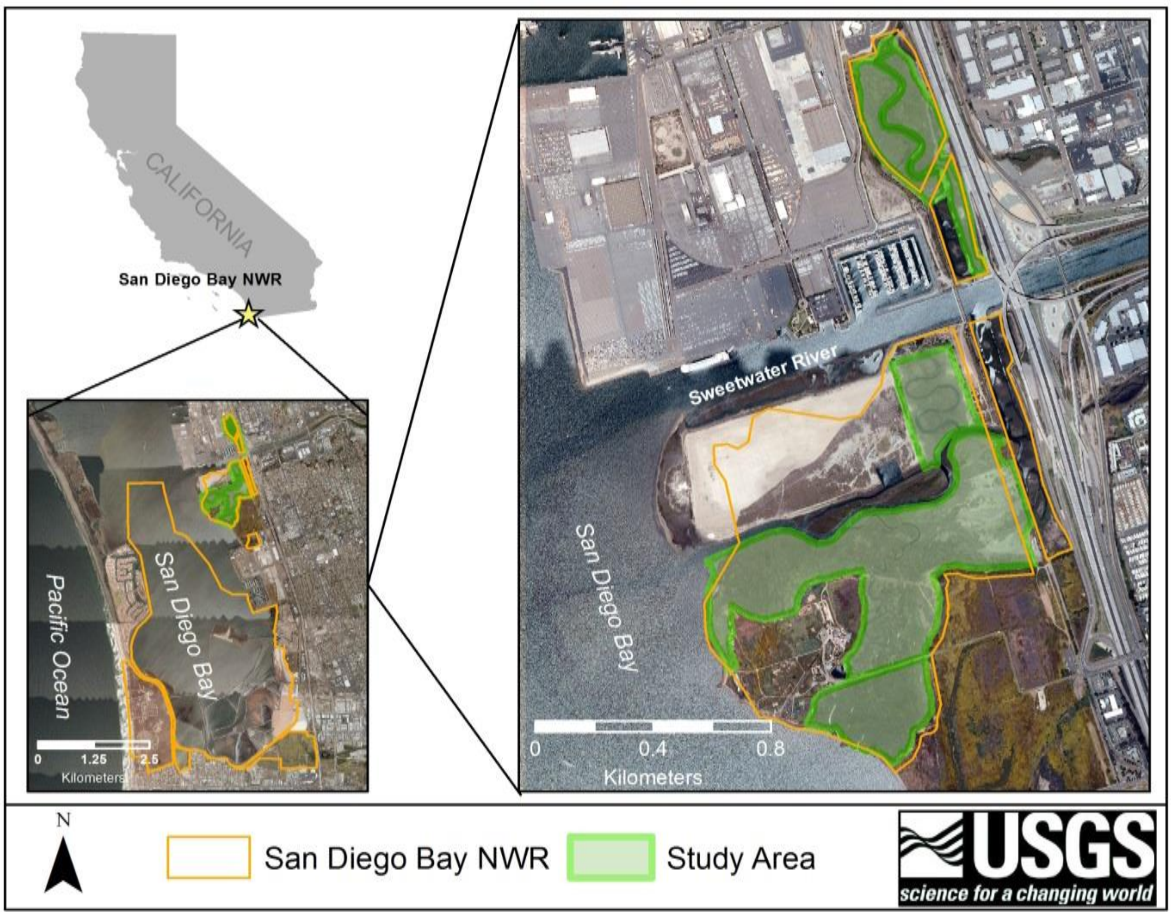

Figure 1. Study area in the Sweetwater unit which is part of the San Diego Bay National Wildlife Refuge complex.

3. METHODS

3.1 Elevation surveys

Survey-grade elevation surveys were conducted at Sweetwater in September 2011 as part of a larger effort to establish site-specific baseline data for the marshes in the San Diego Bay NWR complex (Takekawa et al., 2013). Elevation measurements were taken with a Leica Viva Real Time Kinematic (RTK) Global Positioning System (GPS) rover (accuracy: ±1 cm x, y; ±2 cm z; Leica Geosystems Inc., Norcross, GA, Fig. 2). The rover positions were received in real time from the Leica GS10 antenna base station at the refuge headquarters via radio link. We used the WGS84 ellipsoid model for vertical and horizontal positioning. Positions were referenced to a nearby benchmark with a known elevation height. We surveyed National Geodetic Survey marker S 57 RESET (32° 38' 10.5'', 117° 05' 53.7'') at the beginning and completion of each day to insure consistent and accurate elevation measurements. The average measured vertical error for the benchmarks throughout the study was ±0.023 cm, which is less than the stated error of the RTK GPS (±2 cm). Survey transects were oriented perpendicular to the water, with a survey point taken every 12.5 m; 50 m separated transect lines. The Geoid09 model was used in calculating elevations from ellipsoid to orthometric heights (mean height above sea level; NAVD88; North American Vertical Datum of 1988) and all points were projected to NAD83 UTM zone 11 using Leica GeoOffice (Leica Geosystems Inc., Norcross, GA, v 7.0.1).

Figure 2. Marsh elevation survey conducted with RTK GPS.

3.2 ArcGIS modeling

We synthesized the field elevation survey data to create a digital elevation model (DEM) in ArcGIS 10.2.1 Spatial Analyst (ERSI 2009, Redlands, CA) with Kriging methods (5 x 5 m cell size). The exponential model for Ordinary Kriging was used and model parameters were adjusted to minimize the root-mean-square error (RMS), an internal measure of model performance. The elevation models were then used as the baseline conditions for subsequent analyses including tidal inundation patterns, SLR response modeling, and plant community relationships.

3.3 Vegetation surveys

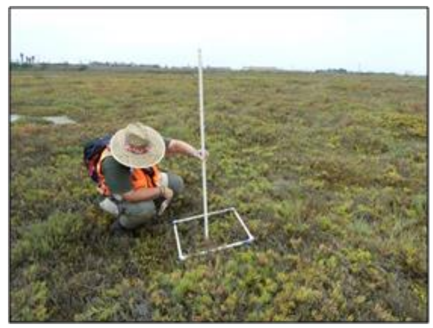

Figure 3. Vegetation surveys were conducted concurrently with elevation.

Vegetation surveys were done concurrently with elevation surveys at approximately 25 percent of the elevation points. The marsh's boundary was used to define the spatial scope using aerial imagery, however during on-the-ground surveys, technicians could shorten or extend transects to adjust for on-the-ground conditions. Vegetation samples were measured at every fourth elevation measurement, but efforts were made to capture edge and boundary vegetation as well. For all plant species within a 0.25 m^2 quadrat, average and maximum height (measured to the nearest 1 cm) were measured visually along with estimated absolute percent cover (Fig. 3). Average height was obtained by visually assessing the most dominant canopy height for each species and measuring a single plant within that canopy. Vegetation data was then combined with our elevation survey data in order to analyze relationships between vegetation species and elevation as well as tidal datum (m, NAVD88). All plant species were categorized into low marsh, mid marsh, high marsh, or upland transition by measuring elevation relative to mean sea level (MSL, m), which was used to relate to changing elevations with SLR.

3.4 Water level monitoring

We deployed two water level data loggers (Model 3001 LT, 0.01 percent FS resolution, Solinst Canada Ltd., Georgetown, Ontario) at Sweetwater (Fig. 4). Loggers were placed at the mouth and upper reaches of second-order channels (tidal creeks) to capture the local tidal cycle and inundation patterns of the marsh. Water level data were collected continuously every six minutes from the fall of 2011 to the summer of 2013 to denote local inundation patterns and hydrographs by season and month. Loggers were surveyed with the RTK GPS at the time of deployment in order to record initial location. Water levels were corrected for local barometric pressure with data from independent barometric loggers in order to standardize measurements using Solinst Levelogger software (Model 3001, 0.05 percent FS accuracy, Solinst Canada Ltd., Georgetown, Ontario).

Figure 4. Water level loggers collected tidal inundation patterns

The local water level data was used to determine elevation and tidal datum relationships. Water level data for a complete year across 2011 and 2012 was averaged to create mean tide level (MTL), mean high water (MHW), and mean higher high water (MHHW) datum relative to NAVD88, values were determined through a comparison to National Tidal Datum Epoch (NTDE). All results were reported relative to local MHW, calculated from local water data (NOAA). In San Diego Bay, where tidal marshes tend to be high marsh platforms, MHW and MHHW are important metrics for understanding the structure and functions of marsh plant communities and wildlife habitats (Takekawa et al., 2011).

3.5 Coring

We measured total sediment and organic matter accumulation at Sweetwater by collecting in-situ soil cores. In cooperation with the University of California Los Angeles (PI: Glen MacDonald, Rich Ambrose), we collected six sediment cores with a Russian peat borer (Fig. 5). Data from the sediment cores were used to calculate annual accretion rates and calibrate WARMER modeling.

Three zones were cored: low, medium, and high marsh areas, with two replicate at each core site. Low, medium, and high marsh areas were determined by RTK GPS elevation and tidal inundation data. Sediment cores were 100 cm deep and 7.5 cm in diameter. In the lab, cores were cut into 1 cm sections and processed for bulk density, porosity, and organic matter composition using loss on ignition, a technique used in organic matter composition analysis, in a muffle furnace at 550ºC (Heiri et al. 2001).

Figure 5. UCLA researchers collecting (top) and examining (bottom) sediment cores collected in San Diego Bay.

We used a gamma ray isotope counter at the Oregon State University Radiation Center to detect Cesium-137 (^{137}Cs) over 24 hours. The radioactivity of each sample was adjusted by its mass to determine a relative measurement. Radioactive fallout from ^{137}Cs was deposited across the landscape prior to 1963 during atmospheric nuclear tests and was attached to soil particles, limiting its movement by chemical and biological processes. Therefore, ^{137}Cs is a unique tracer for studying sedimentation (Ritchie and McHenry, 1990). Lead-210 (^{210}Pb) radioisotope dating is often used together with ^{137}Cs dating techniques to determine accretion rates (Callaway et al., 2012). However, ^{210}Pb deposition is generally very low on the Pacific coast, making detection difficult and requires much longer analysis in the gamma spectrometer, thus we focused only on detecting ^{137}Cs. The depth of the ^{137}Cs peak activity was identified as the 1964 marker horizon, and was used to determine soil accretion rates.

3.6 The Wetland Accretion Rate Model for Ecosystem Resilience (WARMER)

We used WARMER, a 1-D cohort model of wetland accretion (Swanson *et al*., 2013) based on Callaway *et al.* (1996) to examine SLR projections for Sweetwater. Each cohort represents the total organic and inorganic matter added to the soil column each year. WARMER calculated elevation changes relative to MSL based on projected changes in relative sea level, subsidence, inorganic sediment accumulation, aboveground and belowground organic matter productivity, compaction, and decay (Fig. 6) for a representative marsh area. Each modeled cohort provided the mass of inorganic and organic matter accumulated at the surface in a single year as well as any subsequent belowground organic matter productivity (root growth) minus decay. Cohort density, a function of mineral, organic, and water content, was calculated at each time step to account for the decay of organic material and auto-compaction of the soil column. The change in relative elevation was then calculated as the difference between the change in modeled sea level and the change in height of the soil column, which was estimated as the sum of the volume of all cohorts over the unit area model domain.

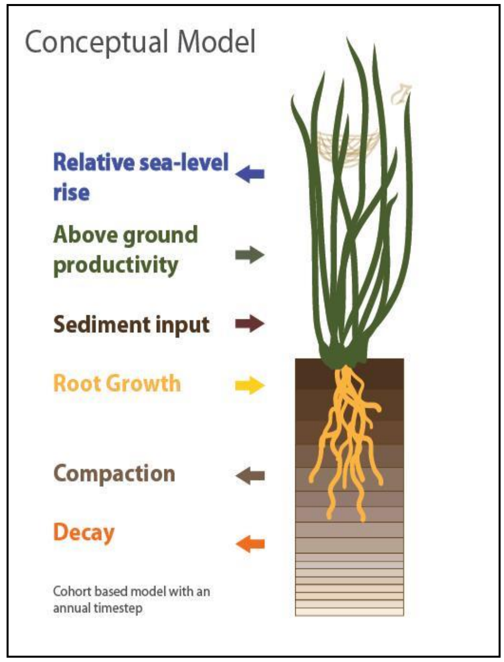

Figure 6. WARMER 1-D conceptual model

WARMER expanded upon the Callaway et al. (1996) model by including (1) feedback between organic matter accumulation and elevation with E(0) adjusting every time step; (2) development of a non-linear relationship between inorganic matter accumulation and elevation; and (3) incorporation of a temporally variable SLR. The elevation of the marsh surface, *E*, at time *t* relative to local MSL was estimated as

$$E(t) = E(0) - SLR(t) + \sum_{i=0}^{t} V_i(t) \quad \text{(Eq. 1)}$$

Where *E(0)* is the initial elevation relative to MSL, *SLR(t)* is the sea-level at time *t* relative to the initial sea level and $V_i(t)$ is the volume per unit area, or height, at time *t*, of the cohort formed during year *i*. The total volume of an individual cohort was estimated as the sum of the mass of pore space water, sediment, and organic matter, divided by the cohort bulk density for each annual time step. Elevation is adjusted relative to sea level rise after each year of organic and inorganic input, compaction, and decomposition. We developed WARMER models from the elevation, vegetation, and water level data collected at each site (see 3.1 - 3.4).

Plant communities were categorized into marsh zones and were related with current elevation to illustrate changing elevation in terms of habitat types to 2110. We defined communities based on elevation by first including only species found in at least five percent of the survey plots across the entire marsh, thus reducing the number of species to eight. A one-way ANOVA was run for species and elevation. We then calculated pair-wise comparisons of elevation by species and determined significant differences using Tukey HSD tests. The elevation mean and SD for statistically similar species were again averaged and plotted as a normal distribution. The range of each community was determined by the intersections of the normal distribution curves among communities. The upper and lower ranges were determined by the mean ±2 SD of the upper and lower community.

3.6.1 Model inputs

Sea-level rise scenario

In WARMER, we incorporated a recent forecast for Pacific coast SLR which projects low, mid, and high scenarios of 44, 93 and 166 cm of rise by 2110, respectively (NRC, 2012). The average annual SLR curve was used as the input function for the WARMER model. We assumed the difference between the maximum tidal height and minimum tidal height (tide range) remained constant through time, with only MSL changing annually.

Inorganic matter

Sediment flux from the water column to the marsh surface at a given elevation *z* was estimated as the product of suspended solids concentration (SSC) and settling velocity summed over all times that elevation *z* is inundated. For the case of constant SSC and settling velocity, the mass accumulation was directly proportional to the inundation frequency and calibrated without any direct measurement of concentration or settling velocity. This sediment flux at a given elevation, z, measured in mass per unit area per year, $M_s(z)$, was equal to:

$$M_s(z) = SSC * w_s * f(z) \qquad \text{(Eq. 2)}$$

where $f(z)$ was the inundation frequency as a function of elevation, and $SSC * w_s$ was the maximum potential sediment flux determined by calibration to sediment accumulation data. Sediment accumulation rates were determined from the 1963 peak ^{137}Cs horizon identified in the soil column and were used to calibrate the sediment input function. The assumption of the model is that accretion rates were limited through time.

Organic matter

The base parabolic organic input function developed by Morris et al. (2002) was used in WARMER. Morris et al. (2002) used smooth cordgrass (*Spartina alterniflora)* as the base of the functional relationship between elevation and organic matter; however, Sweetwater is dominated by pickleweed (*Sarcocornia pacifica)*.WARMER uses an adaptation of the Morris et al. (2002) function where the shape of the function curve for *S. alterniflora* marshes is retained, but the elevation range of the vegetation, the roots of the parabolic equation, and the magnitude of organic matter input are adjusted for Sweetwater vegetation. This was accomplished by fixing the roots of the parabolic function at minimum vegetation elevation and mean astronomical tide (MAT) and the elevation of the peak to the elevation of maximum aboveground biomass. The elevation of peak biomass was determined by analyzing the Normalized Difference Vegetation Index (NDVI) from 2012 NAIP imagery (4 spectral bands, 1 m resolution) and the interpolated DEM. We then calibrated the magnitude of the predicted organic matter accumulation to measured organic matter input rates from the sediment cores. The parabolic equation describing the annual mass of organic matter accumulated per unit area, $\boldsymbol{M_0}$ was then:

$$M_0(z) = (a + b)(z - MSL)(z - MAT) \qquad \text{(Eq.3)}$$

where *a* and *b* are constants with units of $\frac{\boldsymbol{M}}{[\boldsymbol{L^4T}]}$ for above- and below- ground production, respectively, fit to the measured organic matter accumulation rates in the surface layer of each sediment core for each marsh at specified elevations. The organic matter accumulation rate was determined from the sediment accumulation rate and the ratio of sediment to organic matter in the surface layer of each sediment core. Organic matter input was divided between above and below ground input with root to shoot ratio of b/a = 3 based calibration of modeled percent organic matter and bulk density depth profiles to observed profiles from the cores. The mass of organic material generated below ground each year was distributed exponentially with depth and the coefficient of exponential decay, ***kdist***, set equal to 1.0 (Deverel et al., 2008).

Compaction and decomposition

Compaction and decomposition functions of WARMER followed Callaway *et al.* (1996). Compaction of highly porous marsh sediment was determined by a rate of decrease in porosity from the average measured porosity, r, of the top 5 cm of each sediment core and a lower limit of porosity measured at the bottom 5 cm of each sediment core. The rate of decrease, ***r***, in porosity of a given cohort was estimated as a function of the density of all of the material above that cohort:

$$r = 1 - \frac{p_b}{k_1 - p_b} \qquad \text{(Eq. 4)}$$

where $\boldsymbol{p_b}$ is the density of the material above a cohort and $\boldsymbol{k_1}$ was a calibration constant.

Decomposition was modeled as a three-stage process where the youngest organic material, less than one year old, decomposed at the fastest rate; organic matter one to two years old decayed at a moderate rate; and organic matter greater than two years old decayed at the slowest rate. Decomposition also decreased exponentially with depth. The percentage of refractory (insoluble) organic material was determined from the organic content measured in the sediment cores. The constants used to parameterize the compaction and decomposition functions follow those used by Deverel et al. (2008). Model parameters for Sweetwater are provided in Table 1.

Table 1. Model input parameters for Sweetwater. Sediment accumulation rate is reported at the elevation of MSL. NDVI is the Normalized Difference Vegetation Index and NAIP is the National Agriculture Inventory Program.

Model Parameter	Value	Source
Sediment Accumulation Rate ($g/cm^2/yr$)	0.34	Core Calibration
Elevation of Peak Biomass (cm, MSL)	82	NDVI from NAIP
Max. Aboveground Organic Accumulation ($g/cm^2/yr$)	0.032	Core Calibration
Root:Shoot	3	Core Calibration
Porosity Surface (%)	86	Core
Porosity Depth (%)	58	Core
Refractory Carbon (%)	27.3	Core
Maximum Astronomical Tide (cm, MSL)	130	San Diego Tide Gauge (NOAA,9410170)
Historic Sea-Level Rise (mm/yr)	2.06	San Diego Tide Gauge (NOAA,9410170)
Organic Matter Density (g/cm^3)	1.14	DeLaune 1983

4. RESULTS

4.1 Elevation

A total of 1,201 elevation measurements were collected and 1,156 were used in the DEM interpolation process (Fig. 7). The Sweetwater elevation range was 0.83 - 2.74 m with a mean of 1.63 m (NAVD88). Over half (86 percent) of the survey points were located at elevations above MHW (Fig. B-2). A 5-m resolution elevation model was developed in ArcGIS 10.2.1 (ESRI, Redlands, CA) Spatial Analyst using the Kriging method (Fig. 8). The interpolated digital elevation model (DEM) had a low RMS error of 0.11 and a low model mean standard error of 0.12 m indicating the good model fit. This baseline elevation model was used as the initial state in the WARMER SLR model; WARMER results were then extrapolated across the elevation model to determine change through time with SLR.

Figure 7. Elevation and vegetation survey points and water logger locations at Sweetwater in 2011.

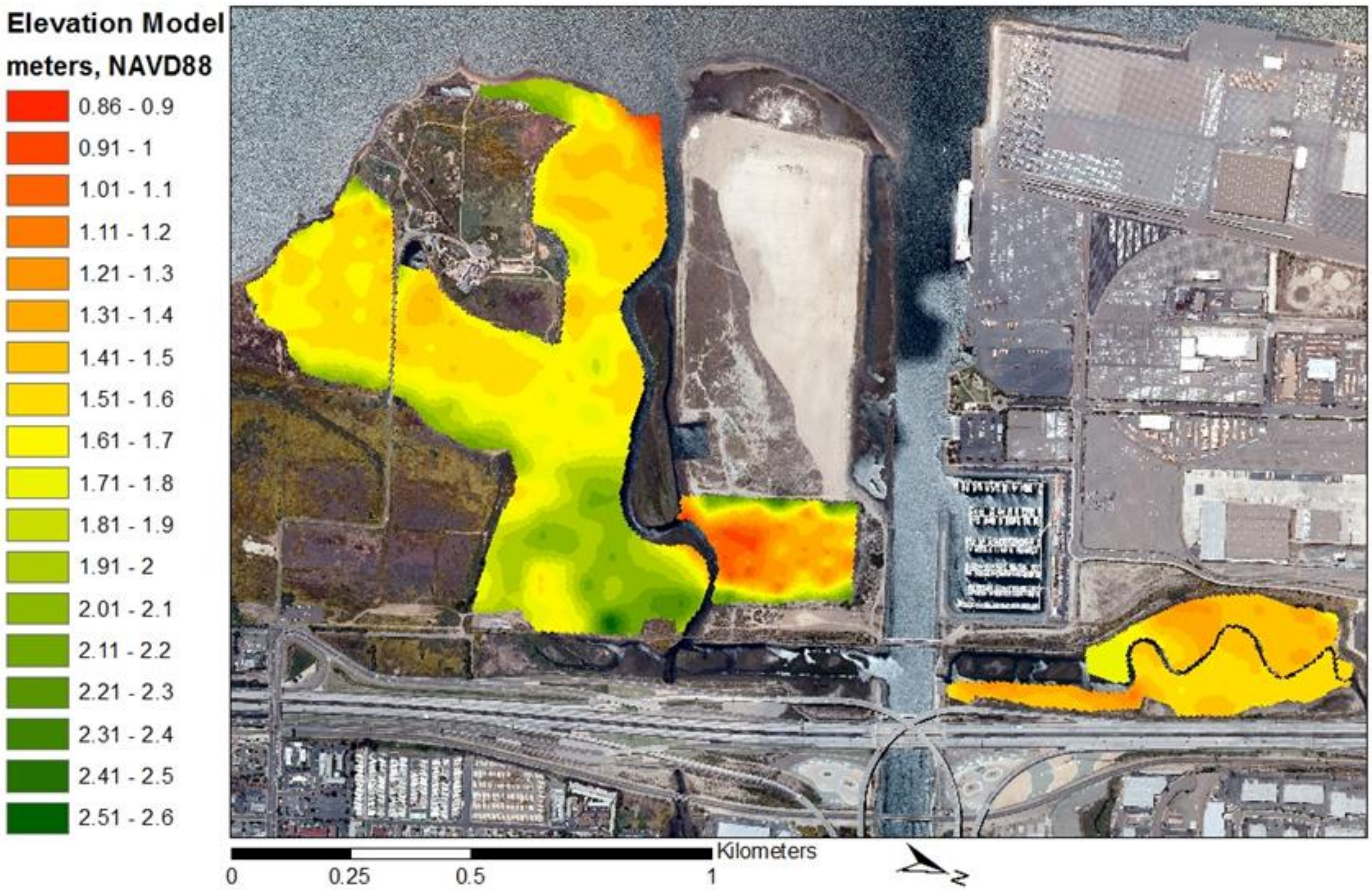

Figure 8. Elevation model (5 m resolution) developed from ground RTK GPS elevation data at Sweetwater in 2011.

4.2 Vegetation

Vegetation data were collected at 274 locations, and 15 species were detected in the marsh (Table 2). The species detected were *Arthrocnmum subterminale, Atriplex watsonii, Batis maritima,* Chloropyron maritimum, *Cressa truxillensis, Distichlis littoralis, Distichlis spicata, Frankenia salina, Jaumea carnosa, Limonium californicum, Salicornia bigelovii, Sarcocornia pacifica, Spartina foliosa, Suaeda esteroa*, and *Triglochin maritime* (Table 3). Distinct zonation in plant communities was observed in relation to MHW because plants are typically restricted by their inundation and salinity tolerance (Figs. 9-11). Only nine species occurred at more than ten percent of the vegetation plots (Figs. 9-11). *Sarcocornia pacifica* was the most common species surveyed across sites, occurring at 64 percent of vegetation plots. *B.maritima* was the second most common species (64 percent), followed by *J. carnosa* (36 percent), *F. salina* (33 percent), *S. bigelovii* (32 percent), *S.foliosa* (27 percent), *L. californicum* (21 percent), *D. littoralis* (21 percent), and *D.spicata* (14 percent).

Table 2. Vegetation species recorded during the Sweetwater vegetation surveys.

Species Code	Scientific name
ARSU	*Arthrocnmum subterminale*
ATWA	*Atriplex watsonii*
BAMA	*Batis maritima*
COMA	*Chloropyron maritimum*
CRTR	*Cressa truxillensis*
DILI	*Distichlis littoralis*
DISP	*Distichlis spicata*
FRSA	*Frankenia salina*
JACA	*Juamea carnosa*
LICA	*Limonium californicum*
SABI	*Sarcocornia bigelovii*
SAPA	*Sarcocornia pacifica*
SPFO	*Spartina foliosa*
SUES	*Sueda esteroa*
TRMA	*Triglochin maritima*

Table 3. Sample number, mean marsh elevation relative to mean high water (MHW), average, and maximum heig percentage cover with standard deviations (SD), and presence by species at Sweetwater. See Table 2 for species code and scientific name.[cm, centimeter; m, meter; n, sample number]

Species code	n	Mean Elevation Relative to MHW (m)	SD Elevation Relative to MHW	Mean Avg. Height (cm)	Mean Avg. Height SD	Mean Max Height (cm)	Mean Max Height SD	Mean Cover %	Mean Cover % SD	Presence (%)
ARSU	25	0.60	0.16	28	12	33	11	68	29	9.1
ATWA	4	0.50	0.05	13	5	15	6	18	22	1.5
BAMA	180	0.02	0.16	13	7	17	8	17	14	65.7
COMA	1	0.53	-	15	-	18	-	30	-	0.4
CRTR	14	0.48	0.11	24	9	27	10	7	8	5.1
DILI	57	0.31	0.21	17	7	23	9	43	40	20.8
DISP	39	0.10	0.15	23	7	29	8	19	20	14.2
FRSA	90	0.22	0.20	18	8	22	9	23	28	32.9
JACA	98	-0.02	0.14	13	6	17	8	37	32	35.8
LICA	58	0.12	0.16	19	9	28	15	18	15	21.2
SABI	87	-0.02	0.16	17	7	23	10	20	18	31.8
SAPA	174	0.05	0.20	25	11	35	14	45	32	63.5
SPFO	75	-0.12	0.16	46	15	62	23	22	17	27.4
SUES	25	0.07	0.12	23	9	30	12	27	23	9.1
TRMA	3	0.03	0.20	11	4	15	5	16	21	1.1

High Occurrence Plant Species

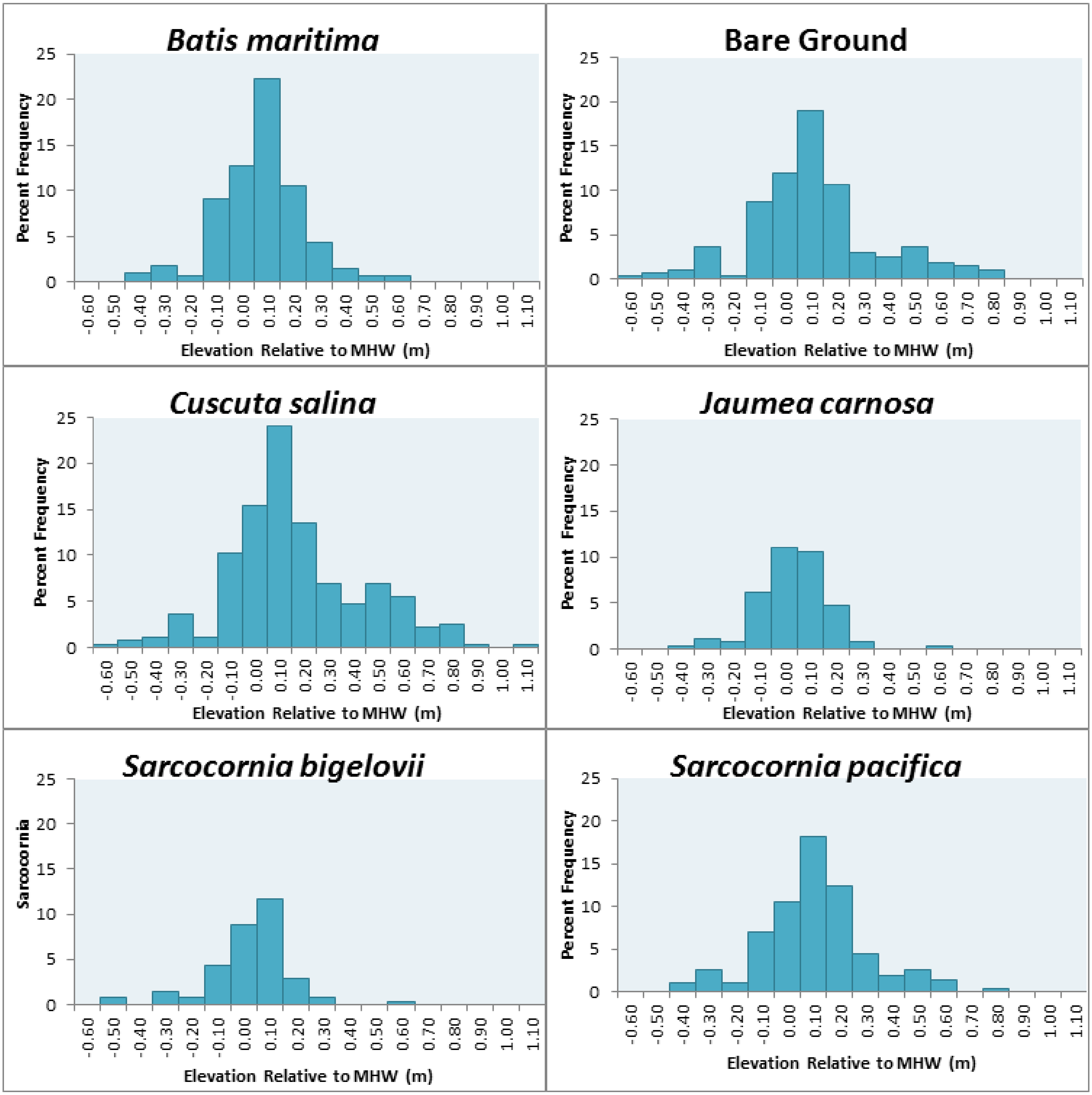

Figure 9. Distribution of high occurrence (scaled at 25 percent frequency) plant species observed relative to MHW across Sweetwater. Bare ground is defined as no vegetation present.

Medium Occurrence Plant Species

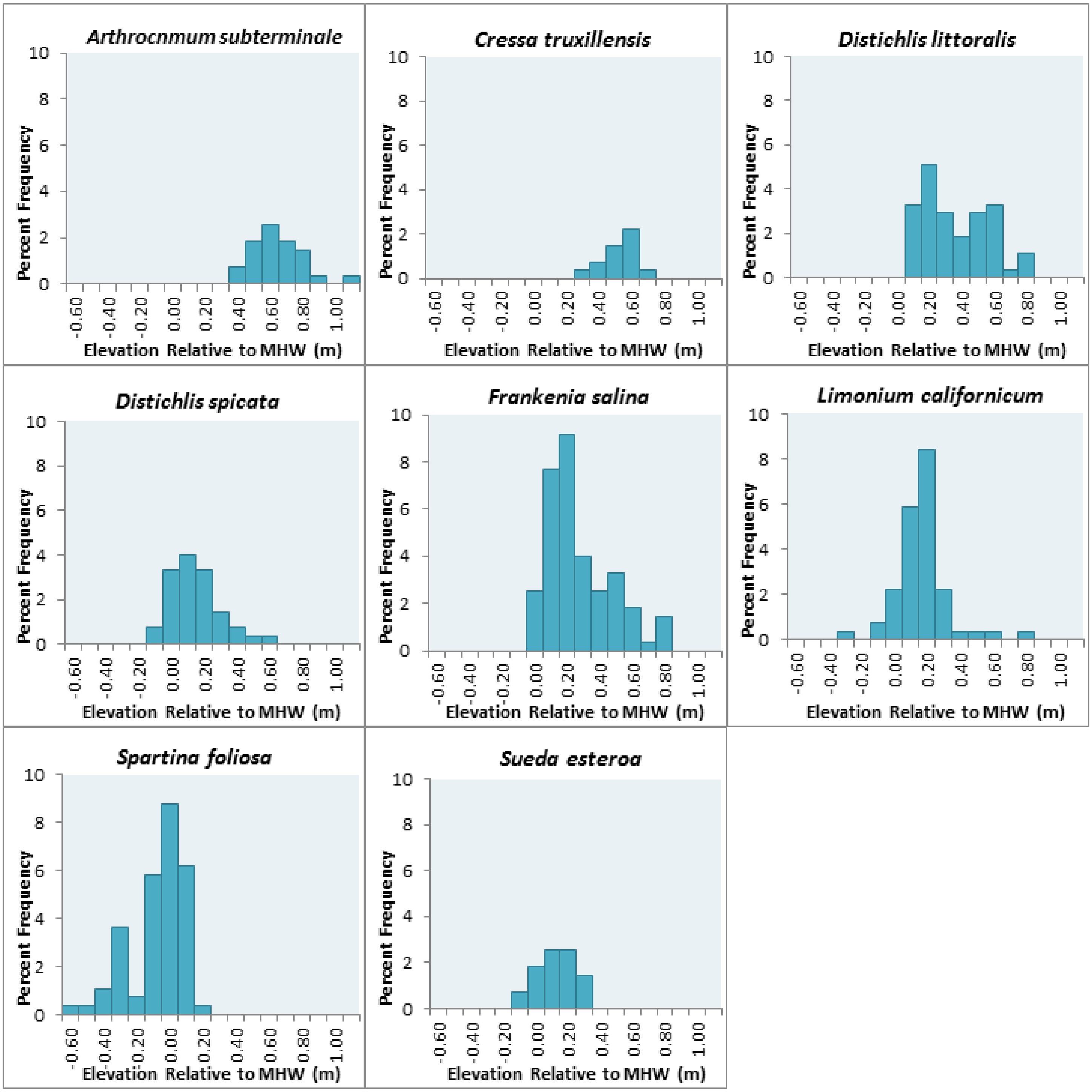

Figure 10. Distribution of medium occurrence (scaled at ten percent frequency) plant species was observed relative to MHW across Sweetwater.

Low Occurrence Plant Species

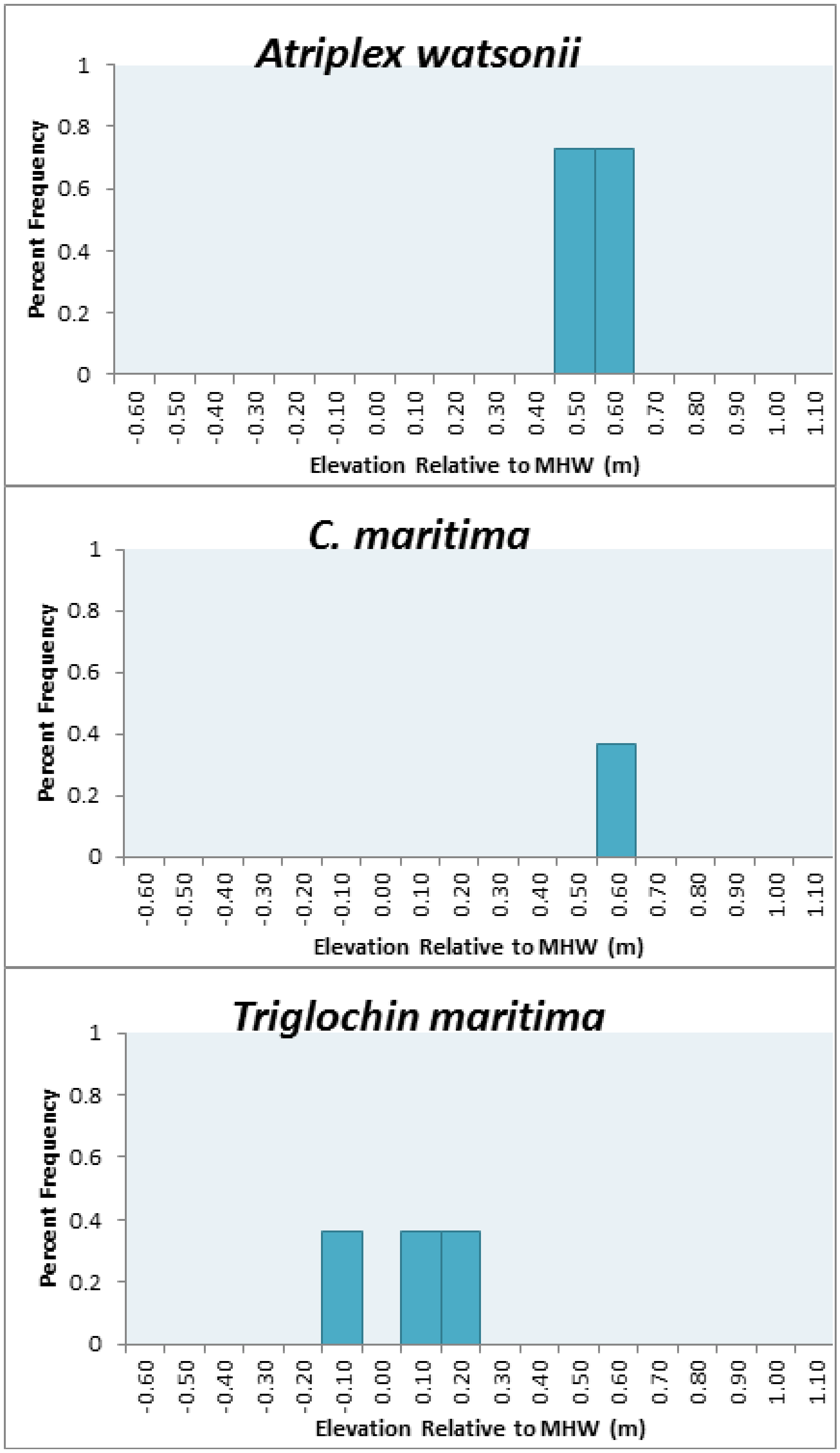

Figure 11. Distribution of low occurrence (scaled at one percent frequency) plant species was observed relative to MHW across Sweetwater.

4.3 Water level

All WARMER modeling results were calculated using a site-specific tidal datum, which was developed using in-situ water level data from 23 September, 2011 to 31 June, 2013 (see methods, Table 4).

Table 4. Sweetwater tidal datums developed from in-situ continuous water level logger data 2011-2013

Datum	Level (m)
Mean higher high water (MHHW)	1.59
Mean high water (MHW)	1.36
Mean tide level (MTL)	0.77

4.4. Coring Results

One core at each of the three elevation sampling stations were analyzed for soil characteristics and dated for ^{137}Cs. The Sweetwater cores were characteristic of tidal marshes in their depth profile, increasing in bulk density with depth while decreasing in organic content (Fig. 12). Mean organic content was low across the cores (10.86% high elevation core, 6.71% mid, 4.93% low). Bulk density increased rapidly with depth across each of the cores (Fig. 12), indicative of the relatively high mineral contribution to the soil column and compaction. Only the low elevation core had a net accretion rate greater than the long-term SLR rate of 2.06 mm/yr (Table 5). The depth profile of bulk density and organic matter content for the mid elevation core was used to calibrate the WARMER model under historic sea-level rise conditions.

Table 5. Soil core analysis results for high, mid, and low elevation sampling stations at Sweetwater. Location is in the UTM zone 11 datum and elevation is in NAVD88. Net accretion rates were calculated by identifying the depth of peak ^{137}Cs activity, which corresponds to 1964, and dividing by 49 years. Cumulative bulk density of organic matter or mineral above the peak ^{137}Cs layer was used to calculate the accumulation rates.

Core	Northing (m)	Easting (m)	Elevation (m)	Organic Matter Acc. (g/m²/yr)	Mineral Acc. (g/m²/yr)	Net Accretion (mm/yr)
2	489995.8	3611791.8	2.09	40.4	559.3	1.6
3	489650.2	3611685.0	1.63	71.7	514.2	1.2
6	489310.9	3611604.1	1.47	60.0	459.5	2.4

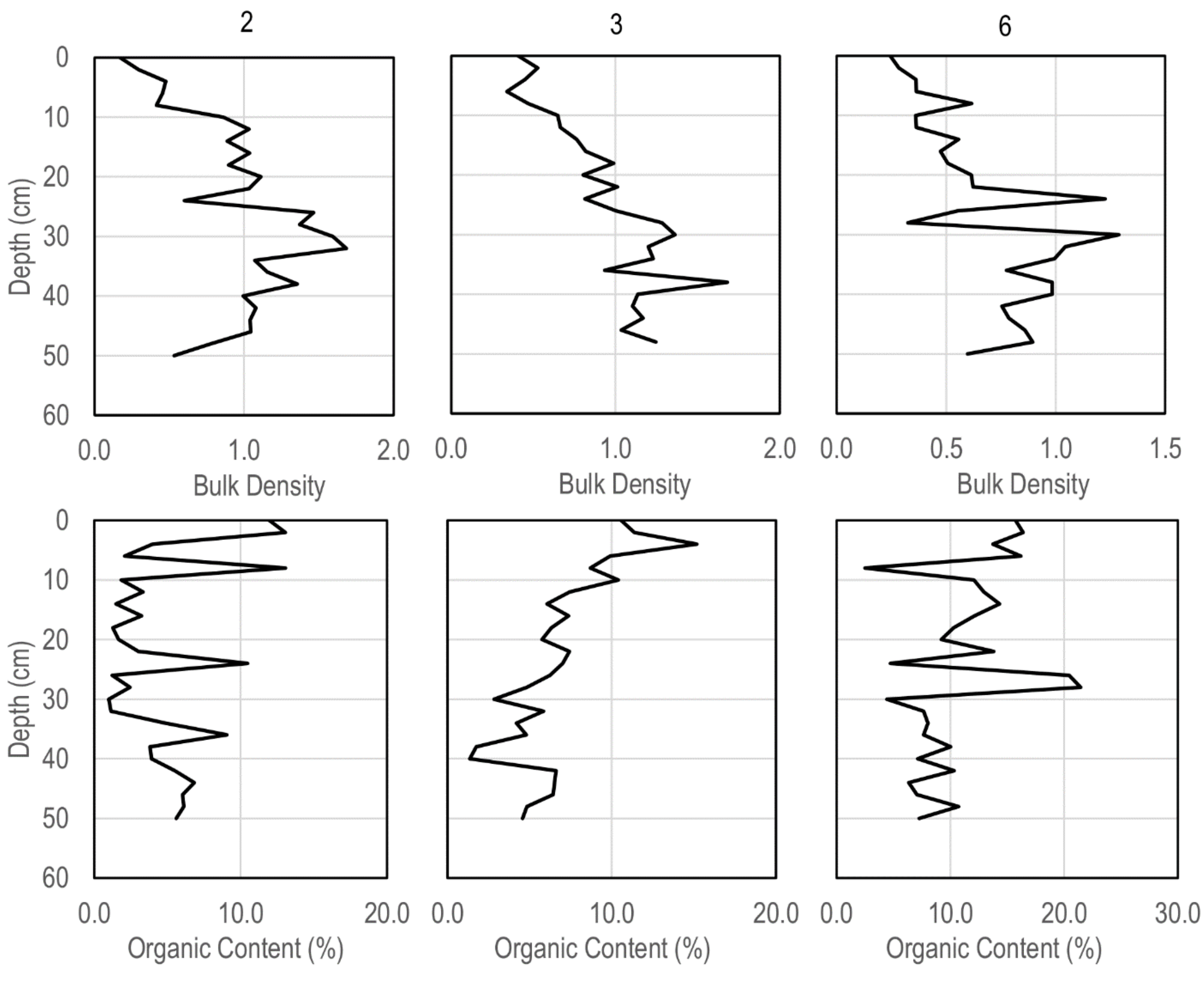

Figure 12. Soil characteristics of 50 cm soil cores (high, mid, low elevation, core 2, 3, and 6, respectively) sampled at Sweetwater. Every other 1 cm core section was analyzed for bulk density (g/cm^3) and organic matter content.

4.5 WARMER Results

The model input parameters used to run the WARMER model were derived using a combination of site-specific calibrations with field data and values presented in the literature (Table 1). Results from WARMER at Sweetwater indicate that elevation relative to MSL will decrease through 2110 under the low (+44 cm), mid (+93 cm) and high (+166 cm) SLR scenarios (Fig. 13).

Plant community normal distributions for elevation were used to distinguish distinct communities for interpretation (Takekawa et al., 2013; Table 6). All plant community elevations were reported relative to MSL. Plant communities were categorized as subtidal (below MLLW), unvegetated mudflat, low marsh, mid marsh, and high marsh based on the elevation of the communities mean elevation (Table 4) and used to interpret the WARMER SLR results (Figs. 13 – 17).

The salt marsh response to and changes in vegetation communities because of SLR varied through time across the low (+44 cm), medium (+93 cm), and high (+166 cm) SLR scenarios. Currently Sweetwater is characterized by a mix of mid and high marsh communities (49 and 33 percent of the area, respectively), with low marsh covering 8 percent and transition and upland habitat covering ~9 percent of the area. Under low SLR (+44 cm) WARMER projected relatively little change in the vegetation communities through 2070, however will transition to low marsh (72 percent of the area) by 2110. Under the mid SLR (+93 cm) scenario, there is little change in the vegetation community through 2040 with vegetation zone percentages relatively comparable to the initial state of the marsh (29 percent, 54 percent, 11 percent for high, mid, and low marsh, respectively). By 2070, low marsh became the dominate vegetation community (60 percent), and by 2110 the area was projected to be a mix of unvegetated mudflats (36 percent) and low marsh (64 percent). Under the high SLR scenario (+166 cm) the marsh was able to keep pace with SLR until 2040. By 2050 low marsh became the dominate vegetation community (55 percent). By 2090, the majority of the marsh is projected to become unvegetated mudflat (75 percent), and by 2110, 8 percent of the marsh falls below MLLW with mudflat dominating the remaining 92 percent.

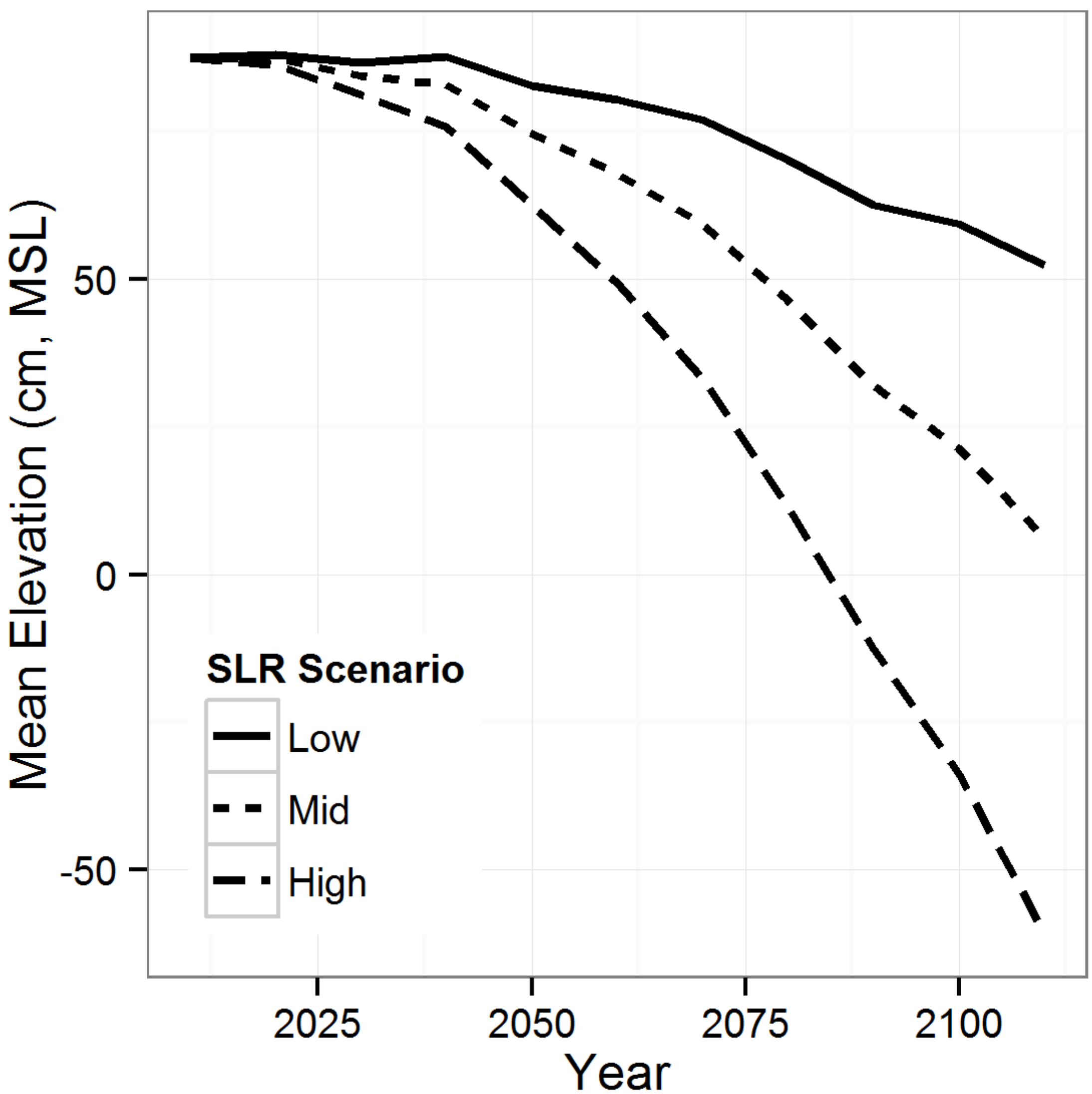

Figure 13. Mean elevation (in cm, relative to MSL) results from WARMER for Sweetwater, 2010 to 2110. Mean elevation for low (solid, 44 cm), mid (dotted, 93 cm), and high (dashed, 166 cm).

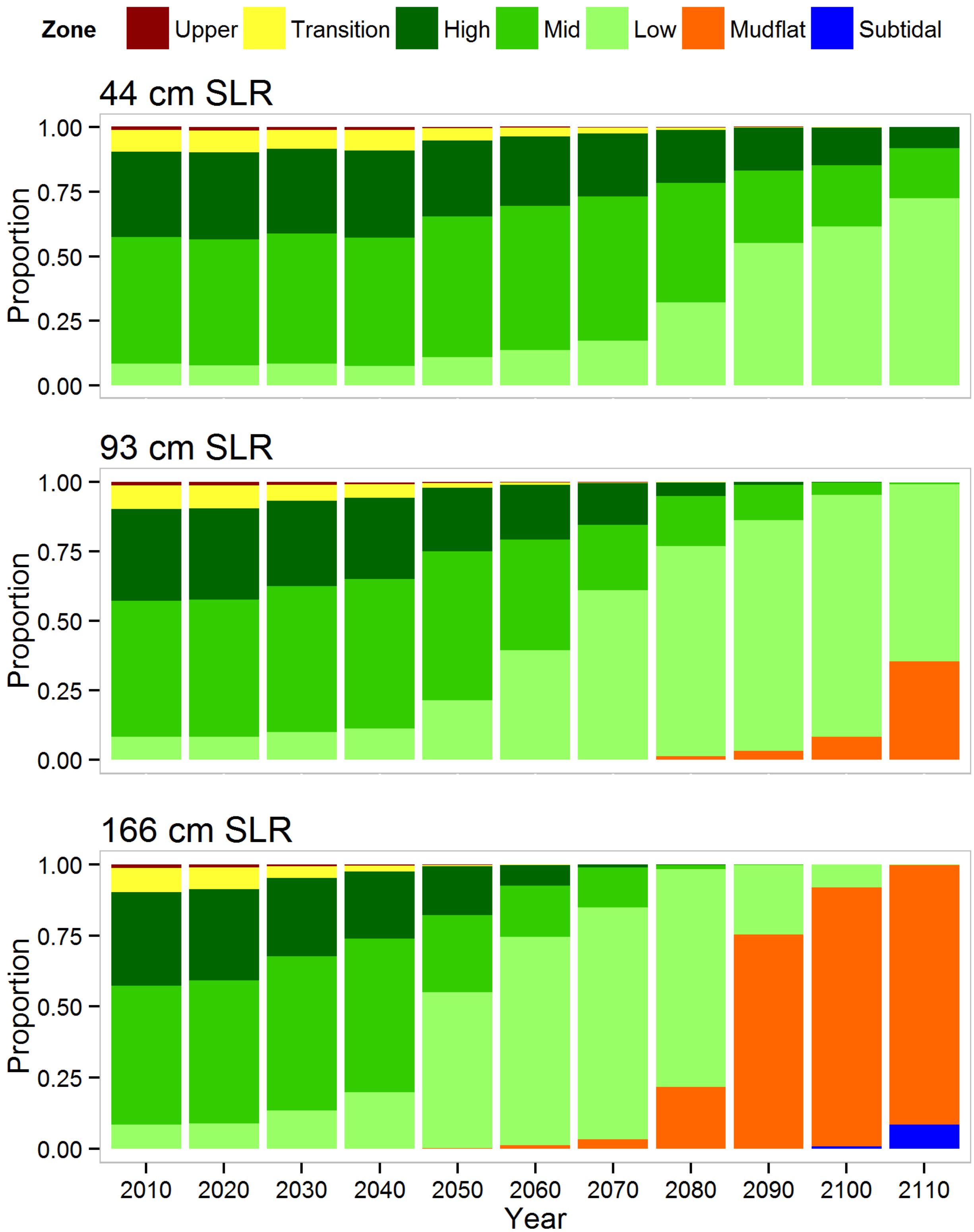

Figure 14. Proportion of area in each plant community under Top) 44 cm, Middle) 93 cm, and Bottom) 166 cm SLR by 2110. High marsh was defined as area above 86 cm MSL, mid marsh 67-86 cm MSL, low marsh 41-67 cm MSL, unvegetated 0-40 cm MSL, and < 0 cm below MLLW (subtidal).

Table 6. Plant community composition and elevation (cm, MSL) at Sweetwater, based on the most commonly observed species (>5% of the survey plots). Values are in cm relative to mean sea level (MSL).

Community	Vegetation Species	Elevation Mean	SD	Community Mean	Community SD
High Marsh	*Frankenia salina*		30.7	91.9	30.7
Mid Marsh	*Jaumea carnosa*	71.5	10	---	---
Mid Marsh	*Sarcocornia pacifica*	69	14.6	---	---
Mid Marsh	*Batis maritima*	68.7	11.4	69.7	12.7
Low Marsh	*Spartina foliosa*	58.7	9.2	58.7	9.2

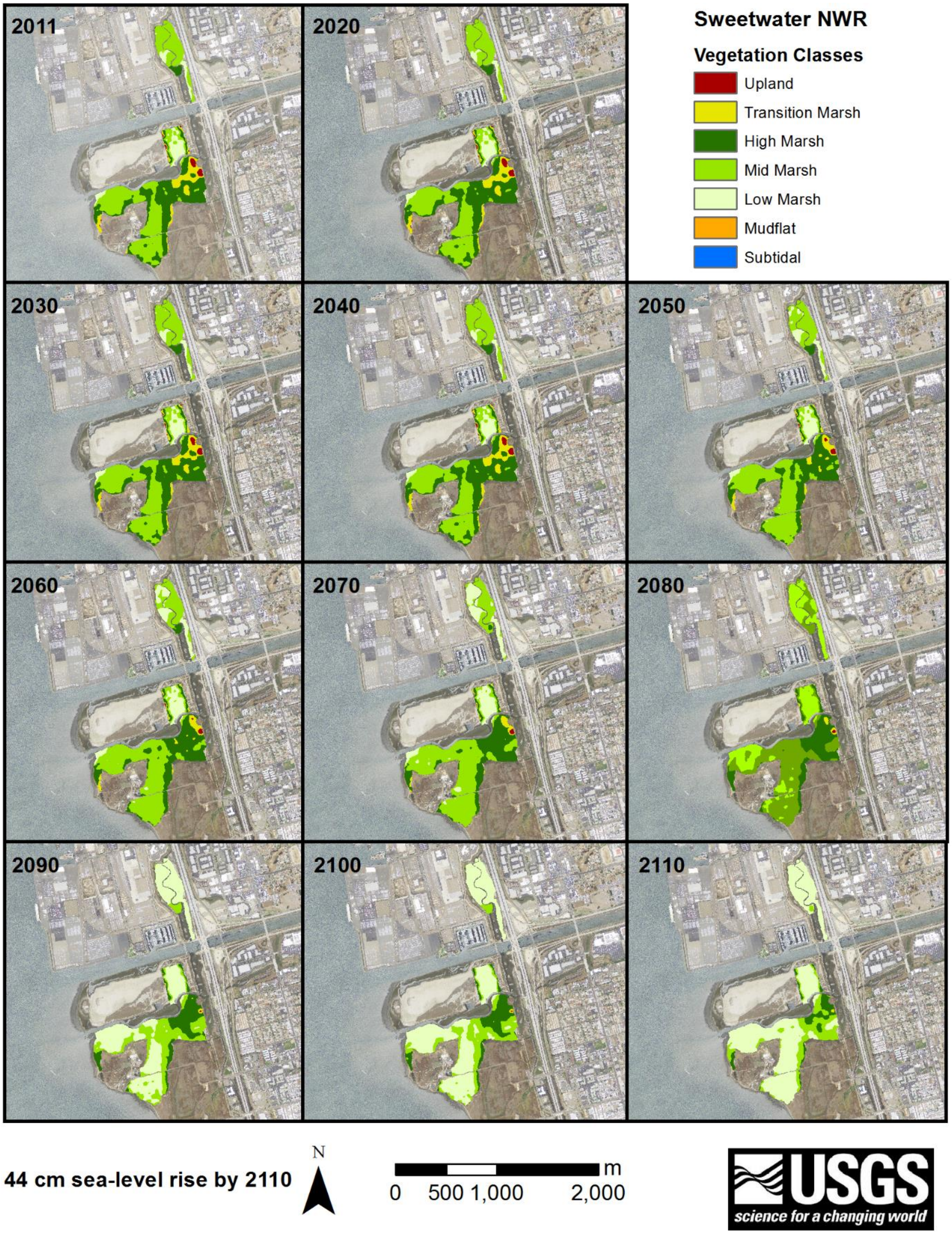

Figure 15. WARMER modeling results for Sweetwater under low (+44 cm by 2110) SLR scenario. WARMER accounts for changes in relative sea level, subsidence, inorganic sediment accumulation, above/below ground organic matter productivity, compaction, and decay.

Figure 16. WARMER modeling results for Sweetwater under medium (+93 cm by 2110) SLR scenario. WARMER accounts for changes in relative sea level, subsidence, inorganic sediment accumulation, above/below ground organic matter productivity, compaction, and decay.

Figure 17. WARMER modeling results for Sweetwater under high (+166 cm by 2110) SLR scenario. WARMER accounts for changes in relative sea level, subsidence, inorganic sediment accumulation, above/below ground organic matter productivity, compaction, and decay.

5. DISCUSSION

The persistence of tidal marshes is threatened when sediment and organic accretion rates are less than the rate of relative SLR. We used site-specific data, including sediment cores, initial elevation, hydroperiod inundation patterns, and vegetation surveys to parameterize WARMER and project marsh elevation change through 2110. We found that under the moderate SLR scenario, Sweetwater is likely to lose 53 percent of mid and high marsh areas by 2070. Under the high SLR scenario, Sweetwater is projected to lose 47 percent of mid and high marsh areas by 2050 and transition to 33 percent unvegetated mudflat habitat by 2080. WARMER projections and modeling results were very sensitive to the SLR scenario used.

Soil core analysis indicates that Sweetwater has very low organic matter contribution to the soil and marsh accretion processes and that net accretion is dominated by sediment accumulation. Marshes with higher productivity may be able to keep pace with SLR (Schile et al., 2014). Radioisotope analysis revealed that the Sweetwater has low accretion rates relative to current rates of SLR (marsh accretion: 1.58 mm/yr; SLR rate: 2.06 mm/yr; NOAA Tides and Currents).

Resource land managers charged with the protection of wildlife species and their habitats are in need of site-specific projections of plant community response to SLR. By identifying the timing of habitat loss with SLR, our research project provides land managers with necessary for making informed decisions and developing climate change adaptation strategies. Resource land managers have limited management options to mitigate projected marsh losses from SLR. Possible strategies can include acquiring upland habitat and initiating marsh restoration. For marshes which abut urban development, sediment augmentation may be an additional viable option (DeLaune et al., 1990).

Like most marsh elevation modeling studies, we were limited to using accumulation rates that occurred under historic conditions for projecting into anthropogenically altered climates. Land use changes, increased runoff, and increased wave-induced sediment resuspension in the future may increase sedimentation rates and reduce marsh loses to SLR. WARMER does not take into account any potential changes to the sediment budget, relying on the historic sedimentation rates for future protections. Increasing temperature and changing salinity conditions may also affect organic matter accumulation rates, however as with sedimentation, WARMER assumes the historic accumulation rate will remain constant. Understanding the impacts of climate change, specifically changes in temperature, precipitation, and salinity on sediment and organic matter accumulation rates is an important direction for future research and monitoring of marsh sustainability.

An increase in the frequency of extreme events may have a greater impact on marshes in the near term (e.g., over the next 50 years) than long-term trends in SLR. Storms can deliver suspended sediment to the marsh surface or cause marsh erosion. Marsh elevation models, including WARMER, do not capture erosional processes. Any losses in elevation, due to increased wave energy for example, are not accounted for in the projections for Sweetwater. Understanding the effects of storms on marsh sustainability is another important future research direction.

Due primarily to low organic matter accumulation and relatively low mineral accumulation, Sweetwater may be at great risk due to future SLR. Development and implementation of adaptive land management strategies may be necessary to protect Sweetwater from the effects of SLR.

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